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VISUALIZATION OF CANNON WEAR USING ULTRASONIC MEASUREMENTS AND MATLAB®

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CUGS (Computerized Ultrasonic Gauging System), the synergistic use of ultrasonic and computer technology, is used to obtain measurements of a gun tube's bore surface. The bore surface is displayed as a "topographical map" whose colors are related to the physical dimensions of lands and grooves. In this manner, bore wear and erosion can be detected as differences in colors. Visualization software is written in the MATLAB® programming language/environment. All aspects of the process are described with special emphasis on the visualization algorithms and techniques. Also described are examples of typical results obtained from CUGS and the visualization software.

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INTRODUCTION

The wear and erosion of a cannon tube's bore surface, i.e., inner diameter, has always been of great concern. The wearing away of material anywhere on or along this surface can detrimentally affect the fatigue life of a tube and/or the accuracy of the associated weapon system. Methods of detecting, predicting, and/or alleviating wear and erosion are very important to the cannon designer, tester, and user.

Ultrasonic measurement techniques (ref 1) have recently been applied to the wear detection problem. In particular, a system denoted as CUGS (Computerized Ultrasonic Gauging System) (refs 2,3) has been used to detect wear in rifled cannon tubes. This is significantly more difficult than detecting wear in smooth bore tubes, since the difference in dimensions between the lands and grooves can cause sound waves to reflect and interfere in unpredictable ways. CUGS uses an on-board computer and specially written software to control all aspects of its operation and is able to scan an entire tube in a remarkably short period of time. CUGS is also able to display a representation of the bore surface by associating the land and groove dimensions with a particular color spectrum. Differences in dimension on the bore surface are then represented as differences in color on the display.

In an attempt to enhance graphical capabilities and increase portability, a method to display CUGS results outside of the CUGS environment was developed. This new display method was developed in the MATLAB® (ref 4) programming language/environment, and relies on the same technique of associating different dimensions with different colors. The purpose of this report is to detail how the visualization of the CUGS data is achieved in MATLAB®. For purposes of this report, a certain familiarity with MATLAB® is assumed; however one can consult References 4 and 5 for additional information.

The next section entitled, "Computerized Ultrasonic Gauging System," contains a brief description of the CUGS system. It is not the intention of this report to describe CUGS in detail, but CUGS is not as well-known as MATLAB® and some familiarity is necessary. References that do describe CUGS in detail have been included.

The third section entitled, "Visualization in MATLAB®," describes how data is displayed outside of CUGS. Special emphasis is placed on two algorithms. The first algorithm determines the center of the tube from the CUGS data. The location of this center is necessary in order to display the dimensions as colors properly. The second algorithm is a color-matching algorithm. The CUGS data is obtained in tube sections. The colors between sections do not always match due to different calibrations for the different sections. An iterative procedure is described that attempts to match the end of one section with the beginning of the next by using one of the calibration parameters.

The final two sections are entitled, "Results" and "Discussion." In the first, typical results from this visualization process are presented. In the latter, conclusions are drawn and future plans are discussed.

COMPUTERIZED ULTRASONIC GAUGING SYSTEM

CUGS represents a synergism of:

- Software controlled electronics, data gathering, calculation, storage, and real-time display
- Squirter technology
- Pulse sensing

It was conceptualized and developed by Reed (ref 2). A lathe supports the tube, and allows it to turn, as a carriage supporting what's called the tool holder moves past. The latter holds the squirter, which in turn contains the 10 MHz transducer where the ultrasonic pulses are generated. The acoustic wave travels along a liquid stream produced by the squirter to enter and return from the outer and inner diameters (OD and ID) of the tube. This arrangement allows the tube surface to travel past the transducer at a rapid rate.

A Matec ultrasonic system containing computer-controlled electronics, with pulser and receiving circuits, is connected to the transducer. The echoes are received and processed by the receiving circuits. An encoder that is mounted on the lathe controls the pulse repetition frequency of the ultrasonic transmitter. As data is taken, the ultrasonic signal generator pulses at the same position around the tube at each rotation, so that the mapping scheme for the tube remains consistent. This is accomplished by means of the encoder, which measures the angular position of the tube as it rotates in the lathe.

The output of the encoder is a digital signal that is used for triggering the pulsing circuitry and as a count for the position. A high resolution Hewlett Packard counter measures the time interval between the firing of the initial pulse and the interface echo (OD) and the interval between the interface (OD) and the first back echo (ID). This information is fed into the computer which controls the operation of the system, records, analyzes, displays, and stores the data in real time.

Since the time measurements are made with excellent resolution (within 1 nanosecond), knowledge of the tube dimensions is limited by the accuracy with which the sound velocity of the particular medium (water and steel) is known (between 0.1 and 0.01%). The three-dimensional bore is then represented in two dimensions, in the manner of a topographical map, where the radius dimensions are mapped to a scale using color.

Sometimes due to storage requirements and sometimes due to OD dimensional changes, the tube is divided into sections. Each section is then measured independently. This requires a new calibration to be performed for each section, since CUGS requires a calibration before each new measurement. One of the calibration parameters to be determined at this stage is the distance from the transducer to the center of the lathe. This parameter becomes important in the next section.

VISUALIZATION IN MATLAB®

Although CUGS has the ability to display its own measurements, a requirement developed to display results off-line, i.e., outside of CUGS. The MATLAB® programming environment was chosen for this task. Besides MATLAB's® well-known ability to perform computations quickly and efficiently, especially matrix computations, it also has a large collection of graphical and imaging functions that greatly simplifies coding the visualization techniques (ref 5). Essentially, after the data has been properly processed, one call to the MATLAB® image function displays the data as desired.

The need to perform several calculations was also necessary. Each circumferential scan has two values per measurement associated with it, a thickness value and an outer diameter value. Each scan can be composed of as many as two thousand measurements, and hundreds of scans are performed on each section depending on its length. For every measurement, an inner radius value is calculated from the other two values. These values are measured from the center of the lathe. Then a transformation must be performed to get the proper values relative to the center of the tube. Finally, the inner radius dimension values must be transformed into a MATLAB® color map and displayed using the image function. Treating all the values obtained in a scan of an entire section as one matrix allows all these calculations to be performed for the entire section at once in MATLAB®.

The center of the tube is not known a priori and must be calculated from the accumulated data for each scan individually. The centroid formula is used along with numerical integration to determine the integrals. In our study, using all the data turned out to give inaccurate results, so only groove data was used to determine the center of each scan.

Distinguishing between land and groove data was a computational challenge due to the effect of the measurements being relative to the center of the lathe and thus off center with respect to the tube. The data was grouped into ten sectors in order to compensate for this effect. Within each sector an average value is found, and values on one side of this average are obviously land data and ignored. Because the remaining data is not obviously only groove data, a second average is found. Values close to this second average are good candidates for groove data so the standard deviation can be computed. Only values within two standard deviations of this second average are used to determine the centroid. This procedure is not exact in many ways. However, it has performed quite adequately, although there were some time constraints when it was first developed.

Since an entire tube cannot be measured at once and is done in sections, slight differences between sections develop. This is because the system must be calibrated each time a new section is measured. The difference between sections is seen as a difference in color when two adjoining sections are displayed in unison.

A Newton iteration scheme (ref 6) was developed in order to match the colors between sections. The average inner radius groove dimension, r, of the last ten circumferential scans of a section is determined. A calibration parameter, normally determined by CUGS, is then found by iteration so that the average inner radius groove dimension of the first ten circumferential scans of the next section is identical to *r*.

The calibration parameter used is the distance from the transducer to the center of the lathe. The functional relationship is complicated, involving reciprocals of square roots of sums of squares. It was not clear that the iteration procedure would necessarily converge for such a complicated function. However, the iteration has never failed to converge to date and the blending of colors from section to section has greatly improved as a result.

RESULTS

Figure 1 presents the inner radius data resulting from one complete scan of a tube's circumference. This figure clearly displays the two main problems associated with visualizing the bore surface of the entire tube. First the data is noisy, typical of most experimental data collecting techniques. Second the underlying radius function of the data is not flat, but curved due to the fact that the measurements are being taken relative to the center of the lathe not the center of the tube.

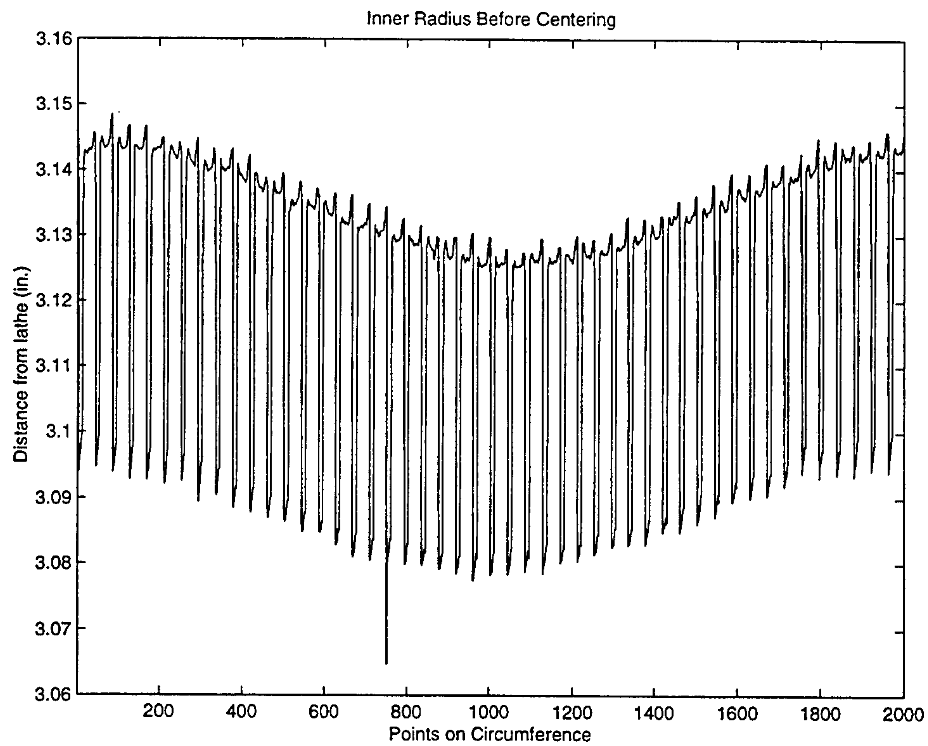

Figure 1. Inner radius data resulting from a complete scan of tube's circumference before centering.

Figure 2 is a representation of the bore surface of an entire tube section. Notice the difference in shading from the left side of the figure to the right. This is due to the curved radius function, not due to any wearing away of the tube. The figure illustrates why it was necessary to find the center of the tube and display the data relative to this point and not the center of the lathe.

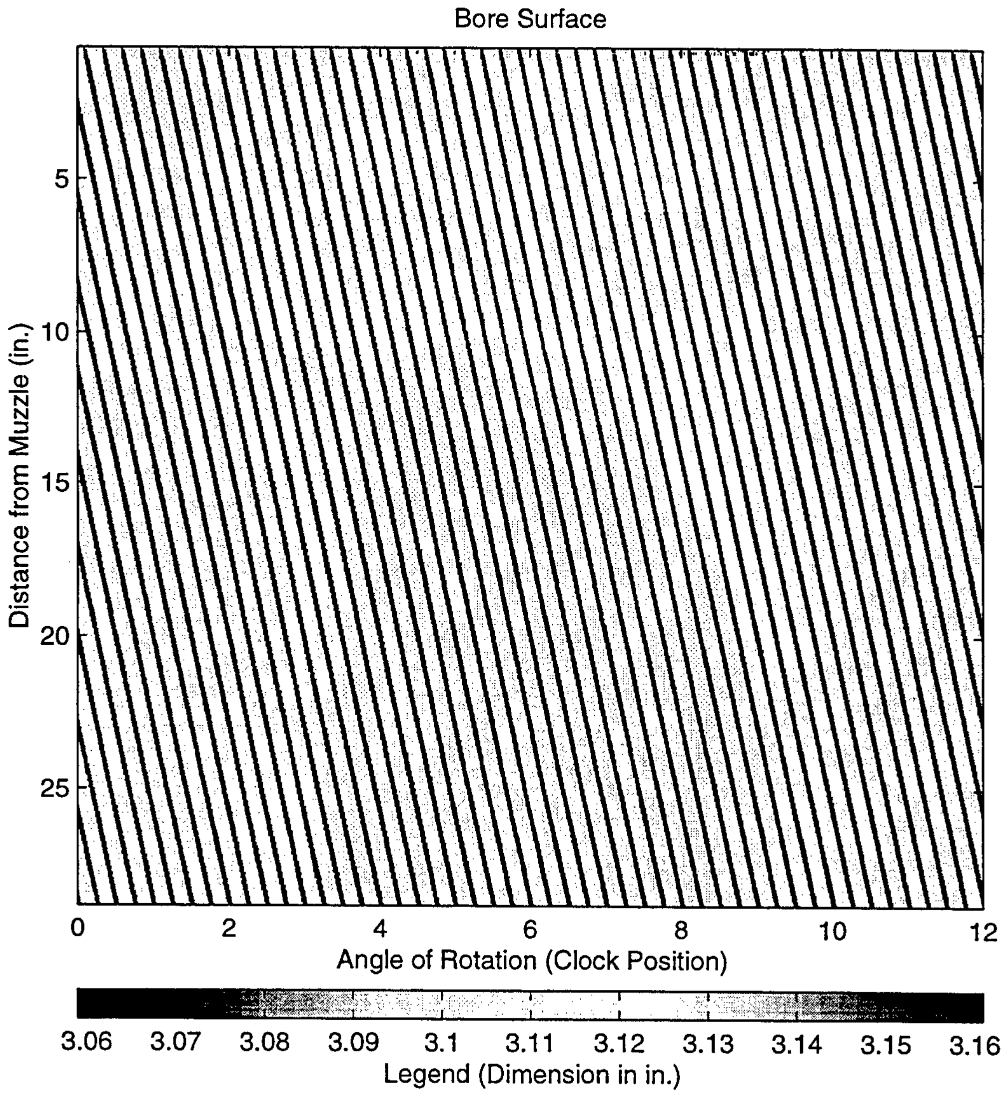

Figure 2. Representation of bore surface of an entire tube section before centering.

Figure 3 shows the inner radius data resulting from one complete scan of a tube's circumference after centering. This figure shows how well a job the centering algorithm is doing as the underlying radius function is now almost flat. Although it is not clear from Figure 3 that the exact center of the tube has been found, perhaps such preciseness is not possible given the data and perhaps not necessary. Figure 4 is a representation of the bore surface of an entire tube section after centering. Notice there is now no obvious difference in shading from the one side of the figure to the other. The precise center of each circumference may or may not have been discovered, but the process has performed well enough so that an observer is no longer deceived.

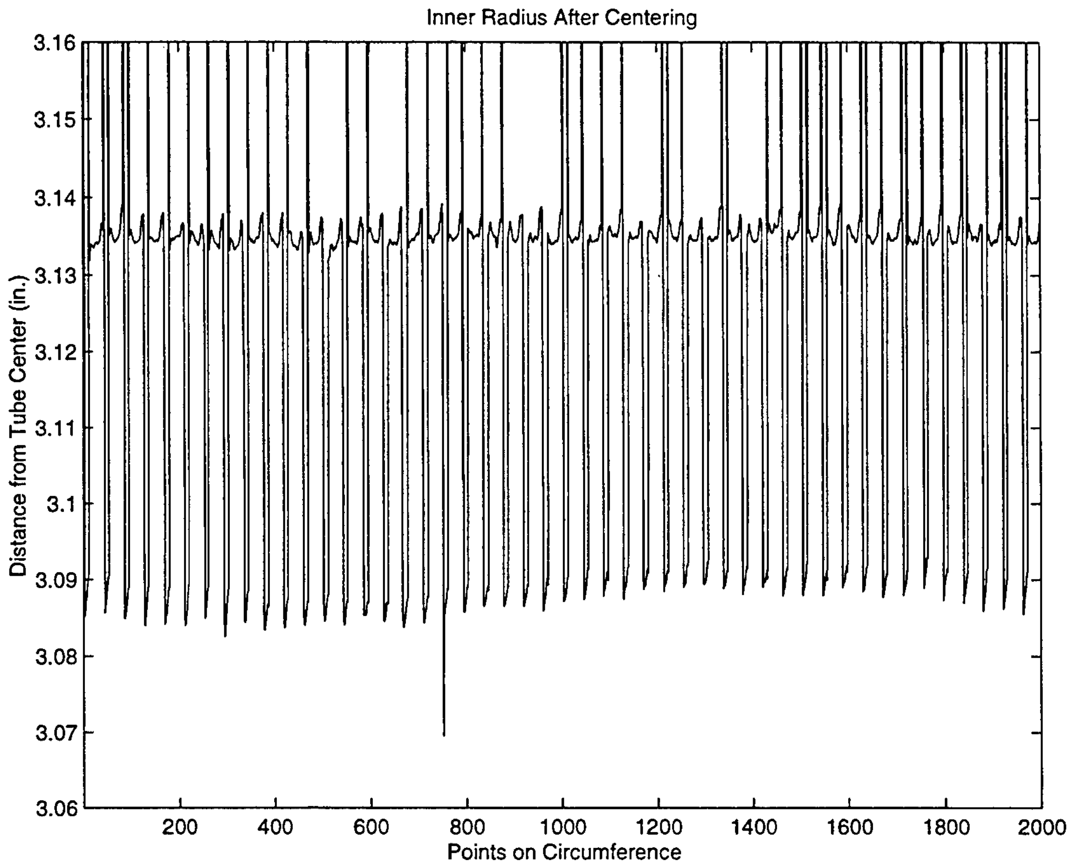

Figure 3. Inner radius data resulting from a complete scan of tube's circumference after centering.

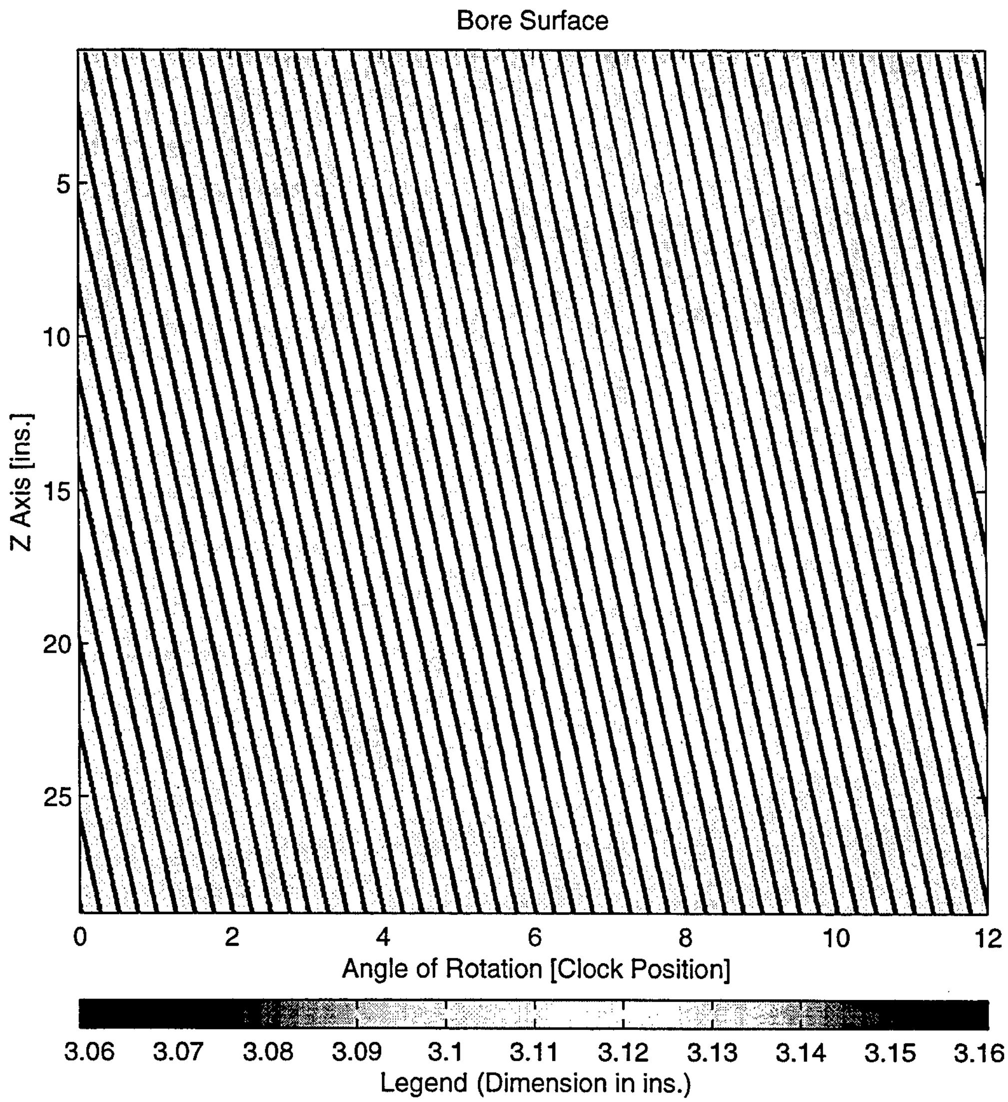

Figure 4. Representation of bore surface of an entire tube section after centering.

Figure 5 shows a representation of the bore surface of an entire tube after centering, but before matching the colors from section to section. Notice the difference in shading from the top of the figure to the bottom resulting mainly from the different calibrations performed on the individual sections since the sections were measured independently. Figure 6 is a representation of the bore surface of the entire tube after centering and after matching. The shading from section to section blends together better in this figure. However, an exact match of colors was not achieved. The iteration did converge for each matched section, so it is felt at this time that the noisiness of the data prevents an exact matching. Better data should result in better bore representations.

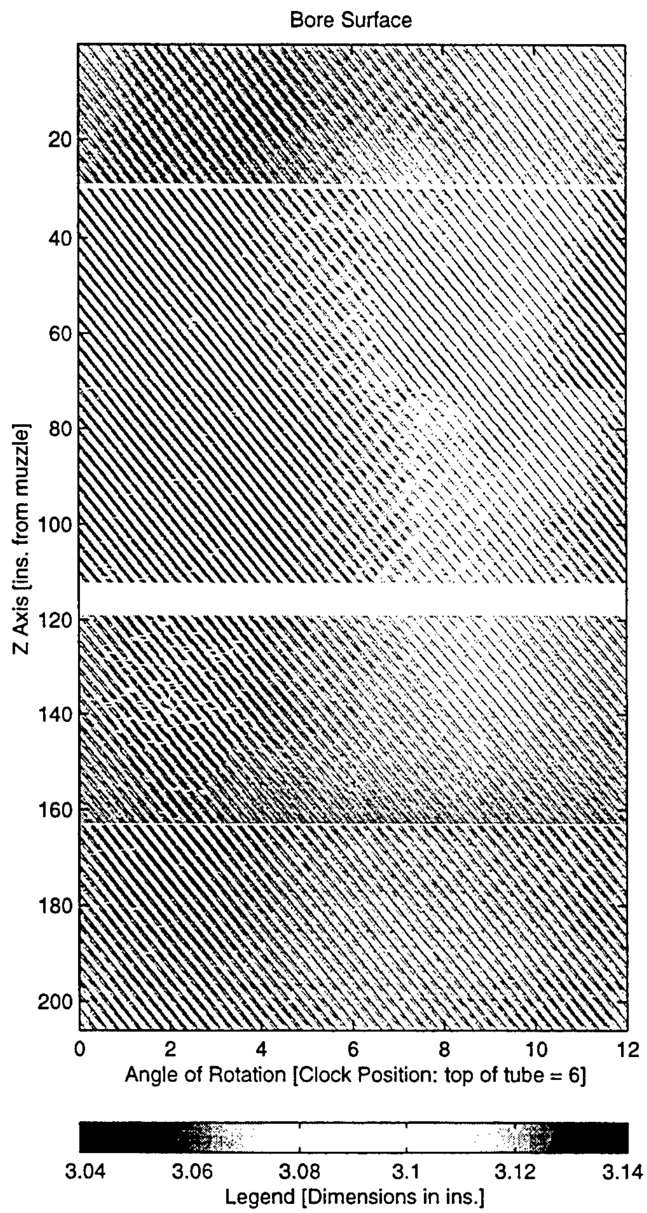

Figure 5. Representation of bore surface of an entire tube after centering, but before matching the colors from section to section.

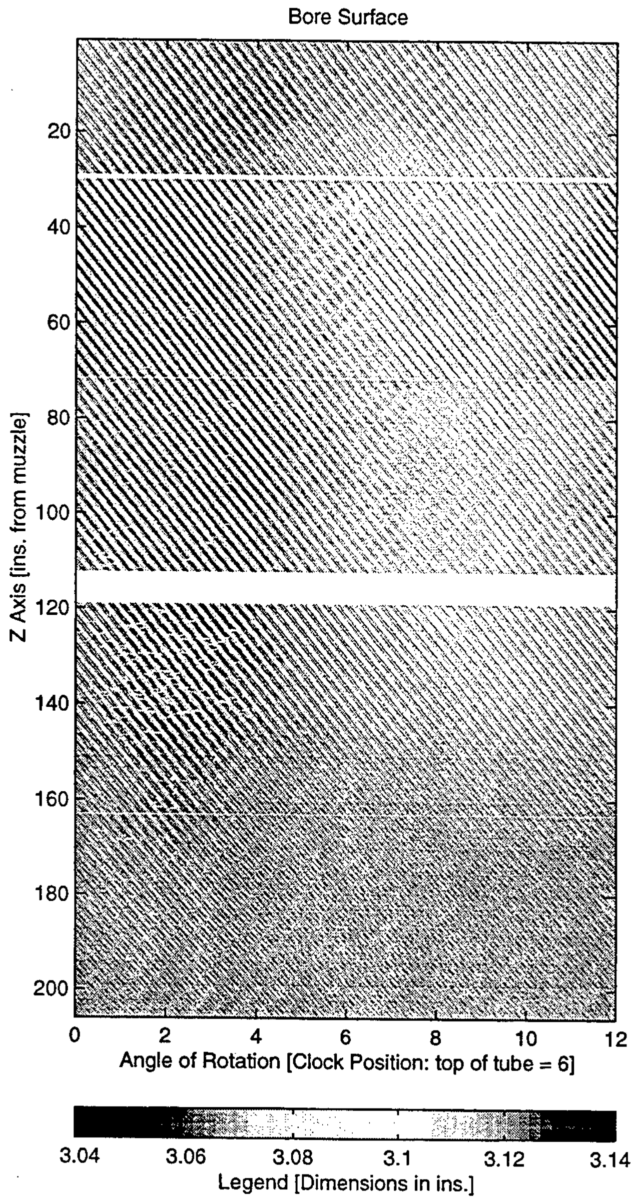

Figure 6. Representation of bore surface of an entire tube after centering and after matching.

In order to indicate the usefulness of this method, Figure 7 presents a representation of the bore surface of an entire tube section with only land data displayed. A wear spot is clearly made visible by this figure. The location of this wear spot has been corroborated by another measuring technique.

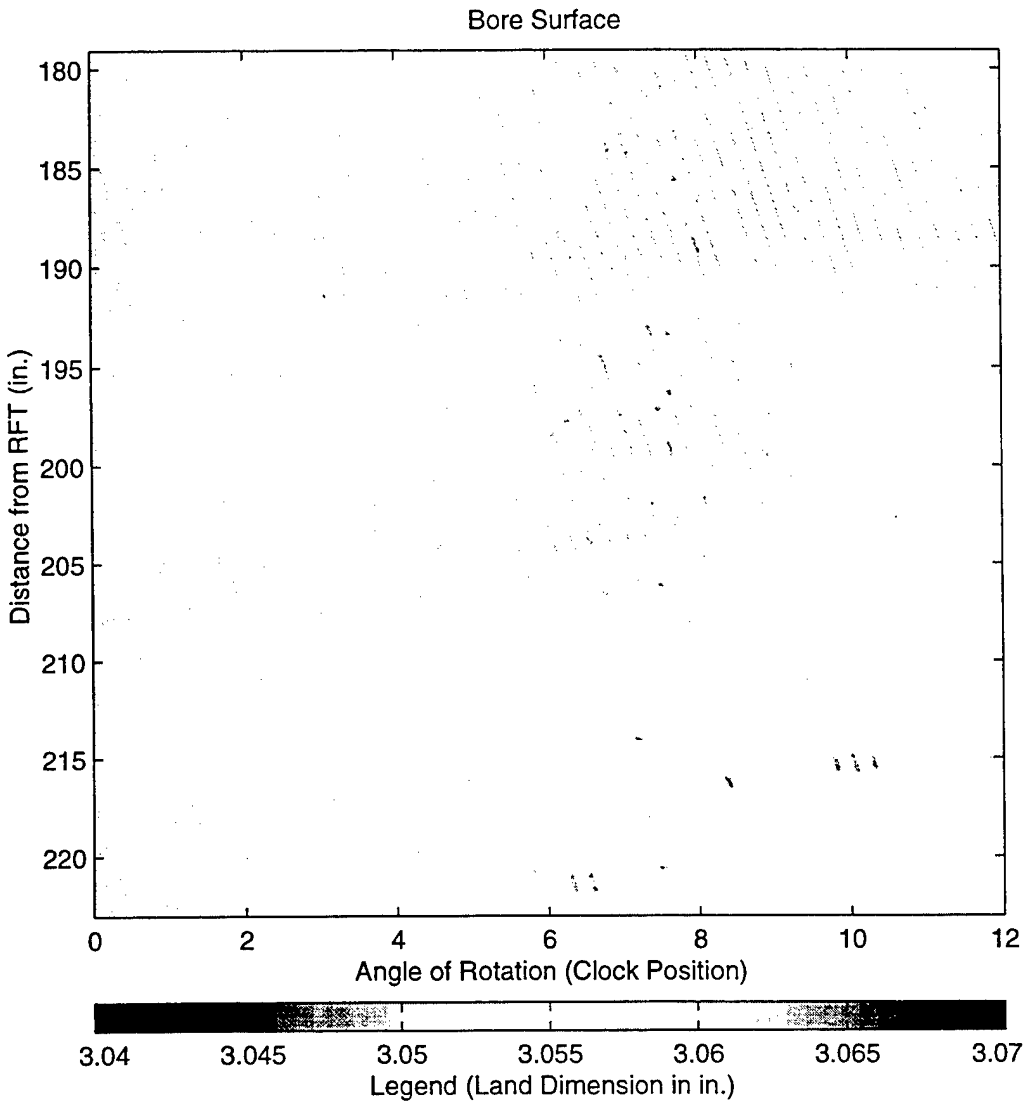

Figure 7. Representation of bore surface of an entire tube with only land data displayed.

DISCUSSION

In many ways, the results are better than expected. The centering procedure seems to be performing well with no significant change in color from one side of a tube to the other (see Figures 2 and 4). This is despite the ad hoc manner in which the algorithm was developed and with no analysis being performed to guarantee or predict the quality of the results.

Differences between section colors have definitely been reduced after the application of the color-matching scheme (see Figures 5 and 6). The matching could, perhaps, be better. However, given the noise in the data and the complicated dependence on the iteration parameter, the degree of success achieved surpassed expectations.

In the future, other centering algorithms will be considered. This is due to the lack of any proof that the centering presented here will work for all data sets. Fortunately, this scheme has performed more than adequately to date. On the other hand, there are no plans to develop any other color-matching procedures. The dependence of the matching on parameters, such as the noisiness of the data and the number of scans being matched, does need to be investigated further.

In general, it seems remarkable that such clear pictures of a tube's bore surface can be obtained in this manner. The minuteness of the dimensions involved, coupled with the dependence on timing and distinguishing between reflected sound waves, seems prohibitive at first. Yet the theory is sound and well understood and the equipment is sensitive enough to produce the pictures presented in this report. Perhaps the figures demonstrate the most encouraging result of all. These pictures are clear evidence that bore wear can indeed be detected and displayed by this method.

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